Working Memory, Attentional Control, and Expertise in Sports: A Review

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Abstract

The aim of the present review was to investigate the theoretical framework of working memory as it relates to the control of attention in sport and thereby apply cognitive psychological theory to sports, but also use the sports domain to advance cognitive theory. We first introduce dual-process theories as an overarching framework for attention-related research in sports. Then a central mechanism is highlighted how working memory is involved in the control of attention in sports by reviewing research demonstrating that the activated contents in working memory control the focus of attention. The second part of the paper reviews literature showing that working memory capacity is an important individual difference variable that is predictive of controlling attention in a goal-directed manner and avoiding distraction and interference in sports. Finally, we address the question whether differences in working memory capacity contribute to sport expertise.

142 words

Keywords: dual-process, working memory, attention, sport, individual differences

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Until fairly recently great athletes were typically described in terms of physical ability so researchers did not pay much attention to cognitive factors involved in sport performance (Starkes, Helsen, & Jack, 2001). On a colloquial level dichotomies like jocks vs. nerds or brain vs. brawn might have kept researchers from studying cognition in sport performance as the physical aspect of sports has far more intuitive appeal than the cognitive aspect. In addition, when looking back at the historical development of psychological research, the experimental information processing approach to cognition forced psychologists to break down large problems and questions about the functioning of the human mind into very small and isolated aspects of cognition (see Mandler, 2007 for a review). As a consequence, each area of research became increasingly specialized to answer ever more specific questions and in turn lost sight of how the individual cognitive components interact in everyday behavior (Styles, 2005). Neisser (1976, p. 7) recognized this problem and stressed that, despite the difficulty of studying cognition, psychologists have to make “a greater effort to understand cognition as it occurs in the ordinary environment and in the context of natural purposeful activity”.

In the field of memory research, a major advance in this regard was made by Baddeley and Hitch (1974, p. 47) with their concept of working memory: “despite more than a decade of intensive research on the topic of short-term memory, we still know virtually nothing about its role in normal human information processing”. Today the concept of working memory is one of the most researched topics currently in cognitive psychology. Working Memory can be defined as the cognitive mechanisms capable of retaining a small amount of information in an active state for use in ongoing tasks (for reviews, see Baddeley, 2007; Conway, Jarrold, Kane, Miyake, & Towse, 2007; Cowan, 2005; Miyake & Shah, 1999). Hence, working memory is of central

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importance to understanding human cognition as it occurs in everyday life and scholars have attributed an important evolutionary advantage to species possessing the capacities of working memory (Carruthers, 2013, Engle 2010). The most important advance of the working memory model was the proposal of a system not only responsible for the storage of information but also for mechanisms of cognitive control and attention (Baddeley & Hitch, 1974, Baddeley, 2003) which made the model applicable to complex behavior.

In the present article we build on the progress that has been made in cognitive psychology by reviewing research on the special cognitive component working memory, especially as it relates to attentional control, to enhance understanding of sport performance. We not only attempt to apply cognitive theory to the sports domain, but also use the sports domain to advance cognitive psychological theory (Moran, 2009; Moran & Brady, 2010).. By adopting dual-process theories (Evans & Stanovich, 2013a; 2013b; Furley, Schweizer, & Bertrams, 2015; Kahneman, 2011; Schneider & Shiffrin, 1977) as a meta-theoretical starting point, the first section of this paper highlights the close relationship of working memory and attention and argues that this relationship can be considered a central cognitive mechanism in the control of attention in sports (Furley & Memmert, 2013). In the second part of the paper we use individual differences in working memory capacity and sport expertise to shed further light on attentional control in sport and follow the call of Cronbach (1957) who argued that the richness of human behavior can only be fully understood by combining experimental and differential approaches to psychology.

Dual-Process Theories and Sports Performance

Numerous theories propose that human behavior is controlled by two qualitatively different modes of processing, automatic and controlled processing (Frankish & Evans, 2009; see Furley et al. 2015 for a more detailed account of dual-process theories in sport). These two forms of processing are specified by their reliance on attentional control which can be defined as the goal-directed allocation of cognitive processing resources to internal and external stimuli (Pashler, Johnston, & Ruthruff, 2001).

An influential dual-process model that attempts to establish commonalities of various domain specific dual-process theories is the default-interventionist model (Evans & Stanovich, 2013a). This model distinguishes between *Type 1* processing—defined as both initiated and completed in the presence of relevant triggering conditions—and Type 2 processing—defined as requiring working memory for hypothetical thinking and mental simulation (Evans & Stanovich, 2013a). Importantly, *Type 1* processes are distinguished from *Type 2* processes by the assumption that the response/solution to a problem has become part of its cognitive representation. For example when solving a simple equation like 2+2 or when an experienced track-and-field athlete crosses hurdles during a race. In both cases the solution to the problems is triggered by the context without requiring further controlled processing as it is part of the cognitive representation of that problem. Similarly, certain stimulus configurations on the sport field can automatically trigger a certain response of an athlete, for example if a point-guard in basketball perceives that his defender is too far away from him and therefore takes the open jump shot. The solution has become part of the cognitive representation because of the great amount of practice and learning experiences of experienced athletes.

On the other hand, *Type 2* processes are required either to override a triggered response that is part of a representation or for a response to a novel problem that has never become part of a representation. It is important to note that *Type 2* processes can also be triggered by the context, but only *Type 1* processes autonomously run to completion as the response is part of the cognitive representation. *Type 2* processes might be initiated autonomously but subsequently require working memory engagement to be completed (Thompson, 2013). Further, Thompson (2013) argues that working memory engagement is not an all or nothing criterion, but can vary depending on the task demands. Therefore, *Type 2* processes should be defined along a continuum regarding their demands on working memory.

Successful sport performance often requires *Type 1* processing as time pressure does not allow for the effortful controlled *Type 2* processing. On the contrary, Type 2 processing has the potential to disturb athletic performance as predicted by the *paralysis by analysis* hypothesis (e.g. Baumeister, 1984; Beilock & Carr, 2001; Hardy, Mullen, & Jones, 1996; Masters, 1992)—i.e. skilled performance can be disrupted from directing attention towards monitoring the skill execution. A large amount of practice and training in sports is undertaken precisely to circumvent the limitations of the slow effortful *Type 2* processing and automate behaviors (e.g. Schmidt & Wrisberg, 2004; Williams & Ericsson, 2005) as the cognitive demands during skill execution decrease with continuous practice (e.g. Anderson, 1982; Fitts & Posner, 1967; Schmidt, 1975; Schneider & Shiffrin, 1977). Therefore, highly practiced basketball players do not need to attend to dribbling the ball and instead can use their freed attentional resources for higher order processes (e.g. scanning for open teammates).

Given the importance of autonomous *Type 1* processing in sports it is not surprising that the study of human motor performance has mainly been driven by a “neo-Gibsonian approach with little regard for the relevance of internal representations such as schemata, or cognitive concepts such as Shallice’s SAS” (Baddeley (2007, p. 317). Similarly, Toner and Moran (2014, p. 1) concluded that contemporary theorizing in sports overemphasizes the autonomous nature of skilled sport performance: “instead of relying wholly on unthinking spontaneity to guide their performance, elite athletes appear to alternate between different modes of cognitive processing”.

For this reason, the present review focuses on the involvement of Type 2 processing's "centerpiece" working memory in controlling attention in sports.

Controlling Attention in Sports

Attention can be defined as subsuming all cognitive processes responsible for increasing or decreasing the level of activation of internal or external representations (Desimone & Duncan, 1995; Knudsen, 2007; Pashler et al., 2001; Posner & Petersen, 1990). According to Pashler et al. (2001) attention increases or decreases the level of activation according to both the goals and needs people have and the stimuli that impinge on them. Pertinent to the present review, recent evidence demonstrates a reciprocal relationship between the current contents of working memory and attention. This shows that attention does not only allow stimuli to access working memory (e.g. Atkinson & Schiffrin, 1968) but working memory can also influence the control of attention (Awh, Jonides, & Reuter-Lorenz, 1998; Downing, 2000; Huang & Pashler, 2007; Soto, Heinke, Humphreys, & Blanco, 2005; Soto & Humphreys, 2007, 2008) by modulating the sensitivity of neural circuits in favor of the information currently being processed in working memory (Gazzaley & Nobre, 2012; Knudsen, 2007).

A theory of attentional control that takes both bottom-up sensory factors and top-down working memory factors into account is the *biased competition theory* (BCT, Desimone & Duncan, 1995) of selective attention. Objects in the world and internal representations compete for processing resources, and this competition is biased towards information that is currently relevant for behavior (Desimone & Duncan, 1995). Attention serves to enhance the response of behaviorally relevant neurons as a consequence of this competition. Hence, if an object is preactivated in working memory and later appears in the visual display, this object will have an advantage in the competition for selective attention and is therefore likely to become the focus of attention.

This biased competition theoretical explanation can be transferred to the context of sports as illustrated in the following example: a basketball point guard might not pass to a team-mate under the “hoop” who is waving (stronger stimulus) but instead passes to the shooting guard at the three point line because of the intended offensive play announced by the coach during the last timeout, in which he was told that the team needs open 3-point shots in order to win the game. In a series of experiments (Furley & Memmert, 2013) this biased competition theorizing was transferred and tested in a simulated sport decision-making task. In this experimental paradigm participants were asked to hold an image of a certain player in working memory—which was controlled for by a memory probe task—while engaged in a time constrained decision task, for example, deciding which player to pass to in a schematic team handball or basketball situation. The results showed that an athlete’s attention is guided towards certain team-members who resemble internal templates that are currently being held in working memory, or stated differently, that attention was controlled by a template held in working memory. Interestingly, the attention guidance effect from working memory was especially pronounced in complex situations in which more players were present in the visual array that competed for limited attentional resources. Based on these findings—and a large body of evidence from cognitive psychology and neuropsychology (e.g. Soto, Hodsoll, Rotshtein, & Humphreys, 2008 for a review)—we argue that the link between working memory and attention can be considered a central mechanism in “everyday purposeful activities” (Neisser, 1976) via its function “to program top-down attentional control”. Of relevance in this respect, Moores, Laiti, and Chelazzi (2003; see also Duncan & Humphreys, 1989) review evidence that top-down control signals from working memory representations do not only raise the activity of object representations in the visual scene that match the internal template in some properties, but this activation also spreads to associated representations. A finding in line with this proposal is that words held in working memory direct eye movements towards semantically related images (Huettig & Altmann, 2005). More recent studies (Soto & Humphreys, 2007; Huang & Pashler, 2007) corroborated these findings by showing that verbal items that were activated in the circuitry of working memory facilitated visual search of semantically related visual objects.

Following from the above line of reasoning on the biased completion theory, verbal instructions by for example coaches are likely to gain access to athletes' working memory and in turn have the potential of controlling the athletes' subsequent focus of attention. Coaches frequently give specific instructions and introduce predetermined offensive plays (e.g., American football, basketball, or team handball) in order to reduce the complexity of the game and give guidance to athletes by directing their attentional focus (cf. Williams, Davids, & Williams, 1999). Typically, these offensive strategies include only a subset of players, and the decision maker therefore has to choose from only a limited number of possibilities. For this reason, it is possible that a player who is not part of a tactical instruction or a specific offensive play is unexpected and is not incorporated into the decision-making process. This hypothesis was confirmed in a series of experiments (Furley, Memmert, & Heller, 2010, Memmert & Furley, 2007) showing that attention guiding instructions can lead to important information being overseen in team sports.

The reviewed findings support Kahneman's (2011) claim that an important function of Type 2 information processing is the adoption of "task sets" by programming memory to control attention. A method athletes can use for programming working memory to control attention can be via the internal processes of self-talk and imagery which are processes associated with the domain-specific storage buffers (the phonological loop and the visual-spatial sketchpad) of Baddeley and Hitch’s (1974) model. Self-talk can be defined as an internal dialogue in which the sender of a verbal message is also the intended receiver (see Van Raalte, Vincent, & Brewer, 2016 for a recent review of self-talk in sports). In a very general sense imagery can be defined as the mental creation or re-creation of sensory experiences that appear to the person imagining them (Morris, Spittle, & Watt, 2005). A useful analogy to clarify the proposed mechanism of how self-talk and imagery can program working memory to control attention is a thermostat (Folk, Remington, & Wright, 1994). A thermostat is set to a pre-defined temperature and actives the heating system automatically if the temperature in the environment differs from the pre-defined temperature. In this respect the person controls the thermostat in advance and the control is subsequently executed autonomously without requiring the person anymore. Similarly templates currently active in the circuitry of working memory—e.g. mental images, goals, strategies, tactics, cue words—set attentional control settings in advance and stimuli associated with representations held in working memory will receive attentional processing resources without any further deliberate cognitive involvement.

Integrating Research Findings from the Sports Domain within the Working Memory/Attentional Control Framework.

In this section we argue that the control of attention by the activated contents in working memory might not only apply to decision making situations in sport but might generalize to a whole range of sporting contexts. Although, we acknowledge that this section can be considered mainly speculative it serves the function of stating testable hypotheses and hopefully stimulating future research and applied guidance on how coaches and athletes can "load their working memories" in ways that are facilitative for sport performance.

Internal or external focus of attention. An increasing body of research distinguishes an external focus of attention from an internal focus of attention when learning or performing sports skills (Wulf, 2007 for a review). The external focus of attention focuses attention on the effects of a movement while the internal focus monitors the bodily execution of the movement. Increasing evidence suggests that, in general, an external focus of attention is facilitative for both learning and performance of sport skills in comparison to an internal focus of attention. For example when performing a tennis shot athletes can instruct themselves to watch the rotation of the seam on the tennis ball (external focus) thereby avoiding unwanted conscious monitoring of the technique of the shot (internal focus). Research has shown that this kind of external focus of attention is beneficial for smooth skill execution (Wulf, 2007 for a review). Therefore, certain cue words can be used via self-talk to "load working memory" and in turn induce an external focus of attention that is likely to be facilitative of performance and learning.

Anxiety and attentional control theory. Attentional Control Theory's (ACT, Eysenck, Derakshan, Santos, & Calvo, 2007) main tenet is that human behaviour is controlled by two attentional systems: a top-down system that is guided by activated contents in working memory (goals, expectations, knowledge); and a bottom-up system that is guided by salient stimuli in the environment (Corbetta & Shulman, 2002). A further important assumption of ACT is that anxiety or performance pressure causes an imbalance between these two systems in favour of the bottom-up system, which can probably be considered an evolved mechanism intended to detect threatening stimuli (Eysenck et al., 2007). That is, with increasing anxiety attention to the threatening stimuli increases, probably in order to allow rapid reactions to escape any potential negative consequences for one's wellbeing. In this respect, it seems feasible that anxiety induces worries and ruminations that gain access to working memory and thereby direct the focus of attention toward threatening stimuli. Wilson, Wood, and Vine (2009) found evidence for such theorizing (although it is not clear what the activated contents of participants' working memory were) in the field of sport by demonstrating that anxious participants were more likely to focus on the 'threatening' goalkeeper in a soccer penalty kick than less anxious players.

In this respect it further seems feasible to speculate about ironic effects (Wegner, 1994) that have been shown in the sport performance domain (Bakker, Oudejans, Binsch, & van der Kamp 2006; Beilock, Afremow, Rabe, & Carr, 2001). For example Bakker and colleagues (2006) demonstrated that the instruction "not to shoot near the goalkeeper" during a soccer penalty kick had the ironic effect that penalty takers more often shot close to the goalkeeper. In this regards the attentional guidance effect by the contents of working memory might have caused an attentional shift towards the goalkeeper as the goalkeeper was included in the instruction (although the instruction was not to shoot close to him) which in turn lead to shots being placed closer to the goalkeeper (cf. Wilson et al., 2009). Future research might want to investigate the relationship between working memory, ironic processing and the allocation of attention in sports performance.

Choking under pressure. Similarly to the point above, performance decrements due to paralysis by analysis (Baumeister, 1984; Beilock, Bertenthal, McCoy, & Carr, 2004; Gray, 2004) might also be reconciled by the working memory attention relationship as it seems feasible that working memory not only controls the external focus of attention but also the internal focus of attention. Baumeister (1984) suggests that pressure raises self-consciousness and worry about performing correctly. These self-conscious thoughts will be active in working memory. Studies have shown that self-conscious thoughts induce an attentional shift to monitoring the step-by-step execution of movement in an attempt to stabilize performance (Beilock et al., 2004; Gray, 2004). Paradoxically, instead of stabilizing performance by directing attention to skill execution, studies (e.g. Baumeister, 1984; Beilock et al., 2004; Gray, 2004) have demonstrated that this explicit monitoring of well-learned skills disrupts skill execution, because Type 2 processing is too slow to deal with the real time control of the proceduralized skills.

Psychological skill training: Imagery and self-talk. In line with the thermostat analogy (Folk et al., 1994), one might argue that the activated contents of working memory cannot only control an athlete's attentional focus in situ, but that imagery and self-talk could train an athlete's attentional focus towards task-relevant cues during performance and away from irrelevant cues. This argumentation was first stated by Feltz and Landers (1983) by proposing that mental imagery will train a beneficial attentional set directing athletes' attentional focus during subsequent sport performance. In this respect the working memory attention link has the potential to serve as the theoretical background for the effectiveness of various applied interventions within sport psychology (e.g. self-talk strategies, gaze training, mental practice or goal-setting). The field of sport psychology has been criticized for neglecting to empirically confirm that its interventions are effective (e.g. Gardner & Moore, 2006) which might be partly attributable to the fact that intervention studies are difficult to conduct without a solid theoretical basis from which strong and testable predictions can be derived.

Individual Differences: The Role of Working Memory Capacity in Sports

So far we have highlighted how Type 2 processing "uses working memory to control attention". In the second part of the paper we focus on the question of whether certain people are more skilled at controlling their attention and therefore benefit in situations that require attentional control. In this respect we follow a recent call of Vogel and Awh (2008) who argued that cognitive theory development can substantially benefit from systematically investigating individual-differences instead of treating these as ‘error variance’ (Cronbach, 1957).. Hence, we will continue by reviewing individual differences in working memory to aid further understanding of attentional control in sports performance.

In contrast to the original notion of short-term memory as that capacity to hold an amount of information (e.g., Miller, 1956), complex span measures of working memory capacity (WMC) have emerged over the last decades assessing the attentional processing component (central executive) instead of the storage component of Baddeley and Hitch’s working memory model (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005). These measures have been successful at predicting performance in situations affording controlled attention in the presence of interference and have led to the formulation of the controlled attention theory of WMC (see Engle, 2002 for a review). In a nutshell, this theory states that WMC is a domain general measure, reflecting an individual’s ability to control his/her attention (e.g., Conway et al., 2005; Kane, Bleckley, Conway, & Engle, 2001; Kane, Conway, Hambrick, & Engle, 2007; Engle, 2002).

Previously we argued that a lot of skilled sports performance does not require controlled attention as it can be carried out automatically with little or no reliance on working memory. However, we also made the argument that there are situations in sport that do require attentional control. In this regard, the cognitive psychological literature (e.g., Engle, 2002) suggests that the ability to control attention is especially important during challenging activities in contexts (a) providing concurrent distraction and (b) interference from prior experience or habit.

***WMC in* focusing attention and avoiding distraction in sport**. In regard to focusing attention and avoiding distraction, Furley and Memmert (2012) demonstrated that basketball players scoring high on WMC measures (Conway et al., 2005) were better able to focus their attention on a computer-based basketball decision making task while blocking out irrelevant auditory distraction (Furley & Memmert, 2012, Experiment 1). Hence, WMC remained predictive of controlling attention between different modalities in this sport performance context, as participants were required to attend to visually presented information to decide on a sport-specific tactical decision while ignoring a stream of auditory information presented over headphones. The fact that athletes with a high WMC reported hearing their own first name significantly less frequently in the unattended stream of auditory information shows that they were more successful in blocking out the task irrelevant auditory stream. In addition, the high WMC Basketball players appeared less prone to everyday distraction on the Cognitive Failure Questionnaire (CFQ, Broadbent, Cooper, FitzGerald, & Parkes, 1982) compared to low WMC Basketball players, which supports the suggestion that working memory is important in everyday attentional control. This correlational finding between the self-reported distractions in the everyday lives of athletes and WMC can be taken as indication that the association between WMC and sport performance might transfer beyond computer-based sport tasks as used in Furley and Memmert (2012) to more representative performance contexts. However, direct evidence for this suggestion has not been obtained in the sport performance context to date.

WMC in resolving interference in sports. Athletes are also assumed to need *Type 2* processing (i.e. WMC), when situations demand a different behavior to that which one has become accustomed to, or when the prepotent response triggered by the context is not appropriate—i.e. to resolve response competition and conflict in interference situations. In this

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respect, research from cognitive psychology has shown that people with high WMC have a superior ability to control their attention which they can use for resolving competition between competing action tendencies and action plans (Engle, 2002 for a review). In a first computer-based study within the field of sports, Furley and Memmert (2012) showed that ice hockey players' WMC was predictive of how well they adjusted their decision making behavior to the demands of the situation, instead of relying on an inappropriate, prepotent action plan. Specifically, ice hockey players with a low WMC (measured with the automated operation span task; Unsworth, Heitz, Schrock, & Engle, 2005) more often blindly" followed a tactical instruction from a virtual coach during a simulated time-out, even though it was not appropriate for the game situation. On the other hand, ice hockey players with a high WMC more often adjusted their tactical decision to the demands of the situation instead of "blindly" relying on the instructions they got during a time-out.

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Competitive sports are full of situations in which athletes have to suppress prepotent (automized) responses due to contextual circumstances. For example, team sport athletes usually have dominant action tendencies (e.g. favorite goal corners in soccer or hockey, a dominant feint side in basketball, or a preference for long distance shots vs. driving to the basket in basketball). However, in the days of professional game analyses, opponents will usually be aware of these dominant action tendencies of individual athletes and most likely have been informed about how to defend these players successfully. Given the computer-based findings from Furley and Memmert (2012) it seems appropriate to hypothesize that WMC would also be predictive of resolving response competition in these representative performance context, i.e. athletes not relying on their dominant action tendencies and adjusting their behavior according to the situational demands. Hence, future research has to scrutinize first findings on the association between WMC and attentional control in sports in more representative performance contexts. In this respect a first study by Wood, Vine and Wilson (2015) can be considered an important step in this direction. Wood et al. found that individual differences in WMC could predict those individuals who would experience attentional disruptions and performance decrements under pressure in a Stroop handgun shooting task whilst wearing eye-tracking equipment. Specifically, low-WMC individuals, relative to high-WMC individuals, experienced impaired visual search time to locate the target and sub-optimal aiming behavior indicative of greater attentional disruptions under anxiety conditions. In this respect, the results suggest that WMC is not only a good predictor of an individual's ability to control their attention but can also predict those likely to fail under pressure in sports.

WMC and creativity. A further domain in which the predictive power of WMC has been investigated is creativity (e.g. De Dreau, Nijstad, Bass, Wolsink, & Roskes, 2012). However, this line of research has provided inconclusive results with some studies suggesting that high working memory individuals are more creative as they are more likely to overcome interference caused by automatic, unoriginal responses and therefore better able to break away from an ineffective approach to a problem (e.g. De Dreu et al., 2012; Lee & Therriault, 2013). On the other hand, some studies have suggested that high WMC enables people to "zoom in" the focus of attention and narrow the search in the problem space, and in turn, harm creative thought (Wiley & Jarosz, 2012).

Creativity is assumed to be of importance in sports (Memmert, 2011 for a review), for example, by allowing athletes to come up with new ways of outsmarting one's competitors and opponents. However, a recent study by Furley and Memmert (2015) provided first evidence that domain-general WMC was not associated with creativity in a soccer-specific creativity task. Hence, WMC was not a limiting factor on creative decision making amongst skilled performers. Experienced soccer players did not benefit from a superior WMC in finding creative solutions to soccer-specific situations.

Although, WMC was not predictive of creativity in sports, there is a growing body of evidence highlighting the importance of working memory and attentional control in sports. Therefore, it seems feasible that this capacity might be an important factor contributing to team sport expertise.

Individual Differences: Sport Expertise, Working Memory, and Attention

A major topic of interest is how people achieve high levels of skills in domains like sports, music, or other games (Ericsson, Charness, Feltovich, & Hoffman, 2006; Hambrick, Macnamara, Campitelli, Ullénjj, & Mosingjj, 2016 for reviews). This topic is embedded in the long-standing nature versus nurture debate (e.g. Ridley, 2003) that concerns the relative influence of innate factors versus learning and experience in determining skill level or expertise. “No psychologist has had a greater impact on the public’s view of expertise than Ericsson” (Hambrick et al., 2016) and it is therefore not surprising that his and his collaborators’ perspective (Ericsson, Charness, Feltovich, & Hoffman, 2006 for a review) has also dominated the sports expertise literature. The dominant view within this field has been that expert sport performers gain an advantage by acquiring cognitive skills and strategies through deliberate practice that increase their efficiency of processing information (e.g. Eccles, 2006; Furley & Dörr, 2015). According to Williams et al. (1999), these adaptations are essential because the speed of many sports may exceed the basic information-processing capacities of athletes. This view specifically states that athletes with years of experience in an activity such as team sports only differ in cognitive processing skills directly related to their field of experience and no differences should be observable in "basic" cognitive abilities such as memory capacity, perceptual acuity, or intelligence (e.g., Eccles, 2006; Ericsson et al., 2006; Feltovich, Prietula, & Ericsson, 2006). These findings are embedded in the theoretical framework of "Long-term Working Memory" (Ericsson & Kintsch, 1995) which states that expert performers bypass their natural processing limitations by acquiring special knowledge structures that function as associations between encoded information and retrieval cues in long-term memory. Hence, in order to retrieve the encoded information experts must reinstate the encoding conditions by using the same retrieval cues (Guida, Gobet, Tardieu, & Nicolas, 2012). In this manner Long-Term Working Memory becomes available for expert performers—but only in their specific field of expertise—and enables them to behave adaptively to the situational demands of their performance environment. According to Ericsson, Krampe, and Tesch-Römer (1993) domain specific knowledge is acquired through deliberate practice—"activities that have been specially designed to improve the current level of performance" (p. 368)—and serves to circumvent performance limitations associated with basic abilities, e.g. WMC: "Performers can acquire skills that circumvent basic limits on working memory capacity" (Ericsson & Charness, 1994, p. 725).

However, this conceptualization has been challenged by empirical evidence (Hambrick & Meinz, 2011; Macnamara, Hambrick, & Oswald, 2014) and has been criticized in the scientific literature. While this criticism does not question the importance of deliberate practice in acquiring expertise it suggests that other factors beyond deliberate practice contribute to acquiring expertise—opportunity factors, basic ability factors, personality factors, developmental factors, and genetics

(Hambrick et al., 2016). Of relevance for the present review on working memory in sports we will focus on the basic ability factor of WMC. While Ericsson and Charness (1994) argued WMC would only influence performance in early phases of training it would be circumvented through domain-specific knowledge when expert status was acquired. In a series of studies Hambrick and Meinz (2011) challenged this circumvention-of-limits hypothesis by demonstrating that WMC was associated with superior performance in complex tasks even in expert individuals with high levels of domain-specific knowledge. Hambrick et al. (2016) review further evidence supporting their "building block hypothesis"—expertise is explained by additive effects of domain-general and domain-specific factors—highlighting that the basic ability of WMC contributed additively to the acquisition of expertise in music and Texas Hold'Em poker. This research suggests that in some domains WMC can limit the highest level of performance that a person can achieve, but Hambrick et al (2016, p. 26) acknowledge that WMC might not contribute to expert performance in every domain: "this is not to say that there are no conditions under which WMC and other basic abilities can be circumvented". Hence, we will review evidence on the importance of WMC in sport expertise.

Although we are not aware of any studies that have explicitly tested the "circumvention-of-limits" or the "building-block" hypotheses in the field of sports similar to Hambrick and Meinz (2011), there have been studies investigating the contributions of basic abilities like WMC to sport expertise. Lyons, Hoffman, and Michel (2009) reported no correlation of scores on a standardized cognitive ability battery (the Wonderlic Test) amongst a large sample of aspiring National Football League (NFL) players and their football performance. Based on these findings Hambrick et al. (2016) suggest that Football may be a domain in which cognitive ability does not significantly contribute to success, or alternatively that the Wonderlic Test did not capture WMC or that team-level factors override the importance of individual level factors. On the other hand, a recent study (Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012) reported that professional soccer players had higher scores on a standardized measure of executive functioning which is closely related to WMC (D-KEFS; Delis, Kaplan & Kramer, 2001) than lower level soccer players and a standardized norm population. Intriguingly, test scores of the professional soccer players were also predictive of the goals scored and assists of the tested soccer players two years later (based on a partial correlation of the square root of the goals/assists and the test scores). These findings led the authors to suggest that "many of the required skills in team sports may be translated to general cognitive domains where test results can be compared to a population norm. A good team player could be characterized by excellent spatial attention, divided attention, working memory, and mentalizing capacity." However, the data from Furley and Memmert (2012) did not indicate any differences in WMC between expert athletes and standardized control populations. Given the results of Vestberg et al. (2012) it is surprising that experienced basketball players (Counting Span Score: M =.65, SD =.07) actually performed slightly worse compared a standardized norm population (Kane et al., 2004, Counting Span Score: M = .69; SD = 0.15). Expert ice-hockey players (Automized Operation Span Score: M = 39.82, SD =18.3) did not show any differences compared to a standardized norm population (Unsworth et al., 2005, Automized Operation Span Score: M = 39.16; SD = 17.4). A further study (Memmert, Simons, & Grimme, 2009) did not find differences between expert team sport athletes, expert track athletes, and novices on several attention tasks. In addition, no differences were evident in the spatial storage component of working memory between experienced basketball players and college students with no team-sport experience (Furley & Memmert, 2010).

Currently data on the relationship between sport expertise and general cognitive abilities is mixed (see Furley & Memmert, 2011 on a more detailed discussion of the ambiguous findings) and does not provide sufficient evidence for either the “circumvention-of-limits” (Ericsson & Charness, 1994) or the “building block” (Hambrick et al., 2016) hypotheses of expertise in the domain of sports. Based on the existing evidence we are currently not convinced that expert athletes have superior WMC or other basic cognitive abilities compared to normal, physically active controls. We do not doubt that attentional control is a highly important attribute in certain sport situations but currently the evidence does not suggest that superior attentional control capacities significantly contribute to sport expertise or even that WMC is a limiting factor for successful sport performance. Those sport athletes that are “lucky” to have a high WMC will most likely only have advantages in some sport situations that demand controlled attention as in Furley and Memmert (2012).

Hence, at present it is not warranted to assume that WMC is an important limiting basic ability in sports. Clearly, the requirements of sports are quite different to those of playing chess, the piano, or texas holdem poker and therefore different abilities are likely to be important in different domains. Further, every sport is different and will require a different skill set (e.g. Ericsson et al., 2006) and therefore different abilities might be beneficial for performance. Therefore, general theories of expertise have to take the specific constraints of the performance situations into account and pay careful attention not to over-generalize the implications of specific findings in one domain across all domains as the relative influence of basic abilities and domain specific knowledge is bound to vary across domains. In the field of sport, research on this important topic has just begun and has revealed ambiguous findings. Thus, more research is warranted to illuminate the role of basic abilities such as WMC in superior sports performance and specifically to test competing hypotheses (see Hambrick et al. 2016 for an overview) that have recently been stated in the expertise literature. In this respect, longitudinal studies that assess both domain-specific factors (e.g. deliberate practice) and domain-general factors (e.g. WMC) are needed across different domains.

Working memory training for athletes. Based on the individual difference findings on WMC and sport expertise we will briefly discuss whether athletes might benefit from training their WMC in order to improve their attentional control capabilities as advertised by several companies (e.g. ~~http://www.cogmed.com/executives-and-athletes~~; retrieved on 21.12.2015). Based on recent evidence (e.g. Shipstead, Redick, & Engle, 2012) we would currently not recommend athletes, coaches, or sport teams to invest training time and other valuable resources in computer-based WMC training.

First, the studies reviewed above do not suggest that WMC is a limiting factor for successful sport performance and so far studies have only suggested that working memory training can be an effective intervention for individuals for whom WMC is a limiting factor in everyday life (Klingberg, 2010, for a review). Second, presently the evidence for cognitive enhancements through computerized working memory training is at best mixed, with some studies reporting cognitive improvements after computer-based WMC training (Klingberg, 2010) and others not (e.g., Owen et al., 2010). Anyway, the more important question concerning the present paper is not whether performance on cognitive tests can be improved by training but whether working memory training can improve performance in sports. To date, the evidence does not support the notion that training programs advertised to improve WMC and in turn everyday attentional control among healthy adults improve cognitive functioning beyond the tasks that are actually being trained (Owen et al., 2010). Similarly, previous endeavors to improve athlete's performance via generalized visual training programs have not proven to be successful (e.g., Abernethy & Wood, 2001). Therefore, in consideration of the present evidence on WMC training, coaches would probably be better advised to conduct sport-specific training to enhance performance instead of incorporating computer-based working memory training sessions into their training schedules.

Concluding Remarks

Over 40 years ago Baddeley and Hitch put forth their model of working memory as they noticed that the majority of research on short-term memory was not very helpful in informing everyday activities. In the present paper we review relevant literature highlighting that working memory is helpful for understanding human cognition and functioning in everyday environments and sport. Although working memory is one of the most widely studied topics in psychology (Baddeley, 2007), working memory has not received as much research attention in the domain of human movement and sports. Contemporary theorizing in sports has recently been criticized for overemphasizing the autonomous, automatic nature of skilled sport performance (Furley et al., 2015; Toner & Moran, 2014). By using dual-process theories as a metatheoretical starting point we argue that future research in sport can benefit from a greater consideration of working memory theory and thereby fulfilling a necessity in psychological theorizing by pitting the conscious person against the deterministic situation (Mischel, 1997). In line with the suggestion of Moran (2009) and Moran and Brady (2010) who argued that the field of sports offers a fruitful domain to explore the validity of models developed in other fields, we show that working memory theory not only has its utility in conducting research in complex applied settings, but can also inform evidence-based practice in sports. Currently there is a lack of research on working memory in the motor performance domain and we hope that this review stimulates future research in this area.

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